Femto- and Atto- Second Pulse Generation for Probing Quantum Entanglement

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for

Quantum Aspects of Beam Physics

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Lawrence Berkeley National Laboratory

Outline

- **Femtosecond and Attosecond Pulses : definition**
- **Applications :**
  - phonon dynamics on a surface
  - primary event in vision
  - protein folding
  - particle beam condensates
  - quantum collapse and entanglement in an atomic system
- **Techniques :**
  - scattering
  - optical slicing
  - ponderomotive bunching
  - laser wakefield acceleration
- **Table-top SASE x-ray FEL**
- **Fundamental issues with optical control**

Ideas being developed at the

CENTER FOR BEAM PHYSICS

with contributions from :

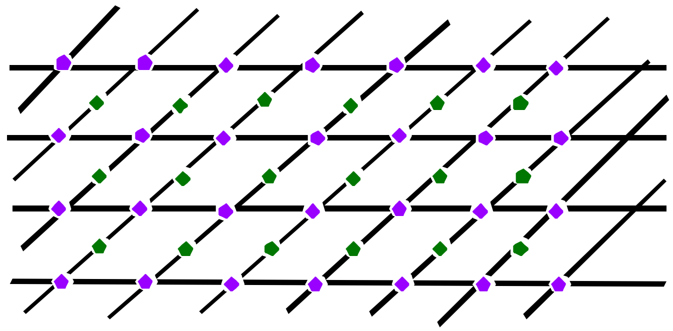
- Swapan Chattopadhyay
- Eric Esarey
- Wim Leemans
- Sasha Zholents
- Max Zolotorev

Attosecond Pulses

10^{-18} seconds $\lesssim \tau \lesssim 10^{-15}$ seconds

allows pump-probe experiments @ 10^{-17} second scale

Phonon Dynamics on a Surface



Lattice vibrations and 'Phonon' spectrum characterized by Debye time-scale :

$$h\nu \approx kT$$

Phonons

Thermal Bath

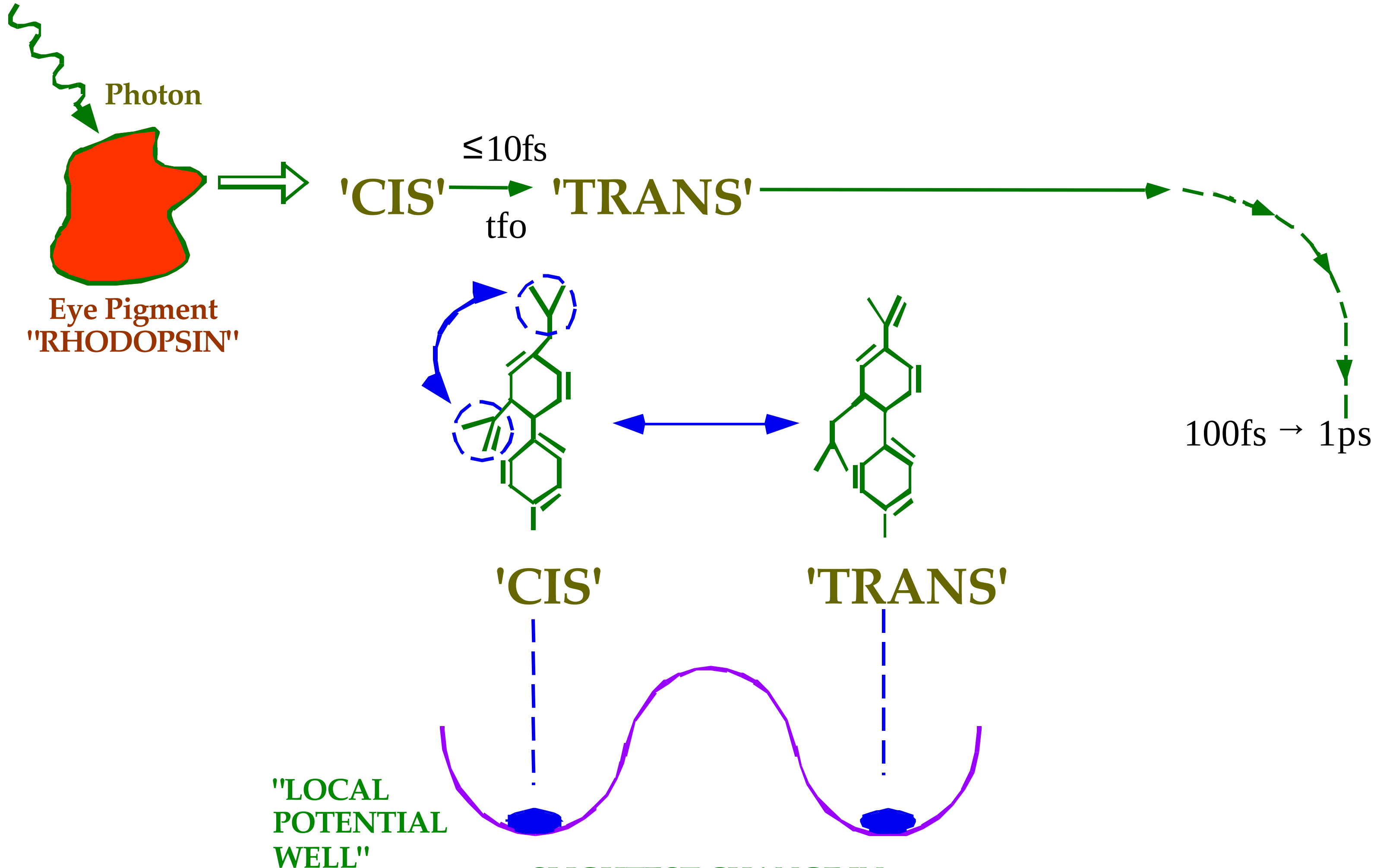
Lattice relaxation time :

$\boxed{\tau = \nu^{-1} = h / kT}$ ~100 fs @ room temp.

e.g. PHASE TRANSITIONS like surface melting etc. take place on these 1 - 100 fs time-scale.
EXTREMELY VALUABLE INFOMATION for SEMICONDUCTOR PHYSICS. e.g. Silicon

Primary Event in “Vision”

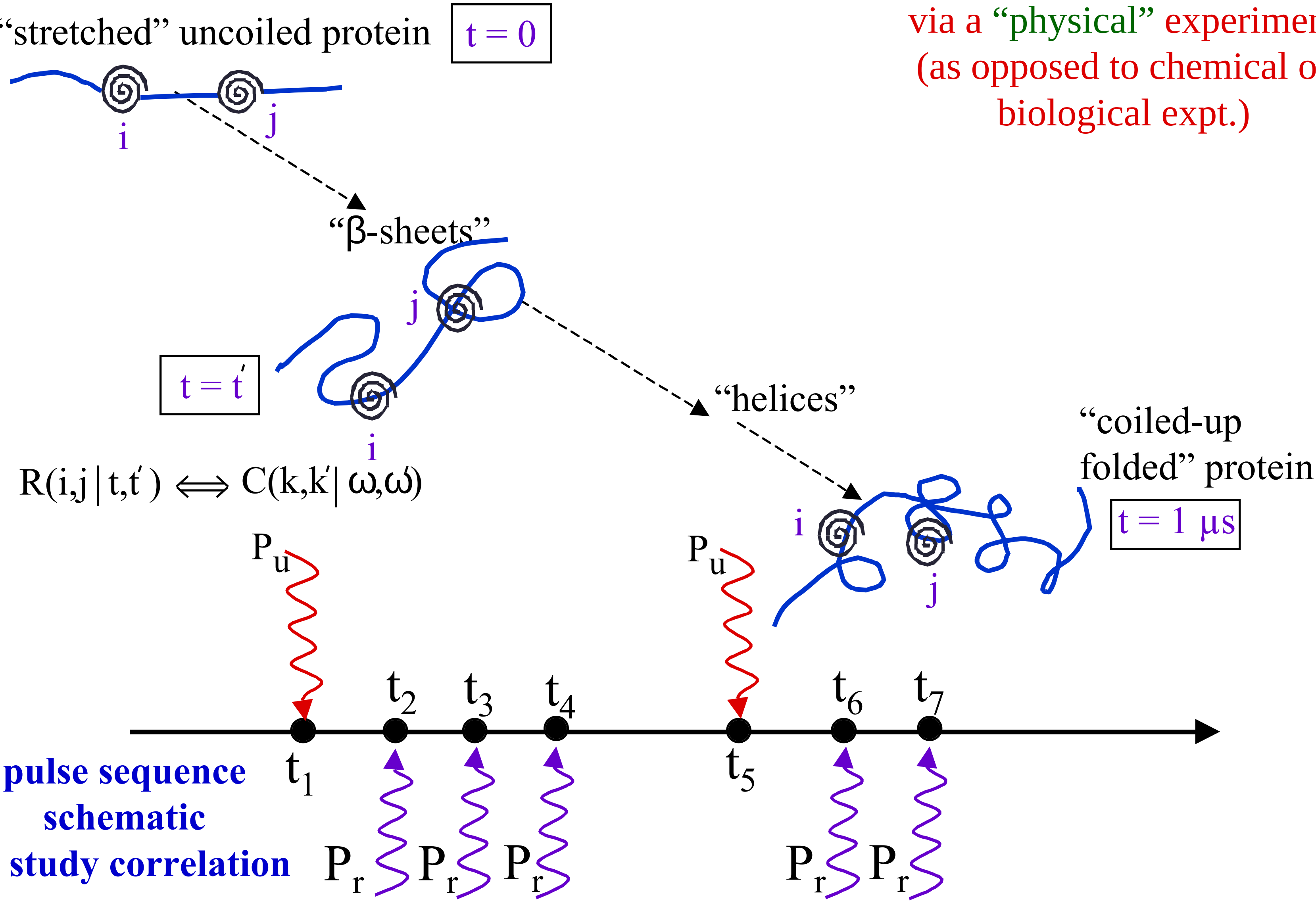
Ultrafast Coherent Chemical Reactions



SLIGHTEST CHANGE IN "STRUCTURE" LEADS TO LARGE CHANGES IN "FUNCTION"

Controlled Study of “Protein Folding”

via a “physical” experiment
(as opposed to chemical or
biological expt.)

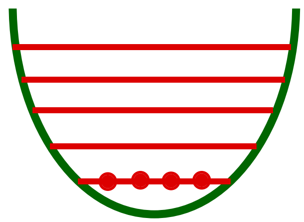


pulse sequence schematic to study correlation

Particle Beam Condensates

Beams of BOSONS and FERMIONS at the limit of quantum degeneracy where quantum mechanical collective behavior is important. Can one ever cool particle beams to the limit of such **"condensates"** ??

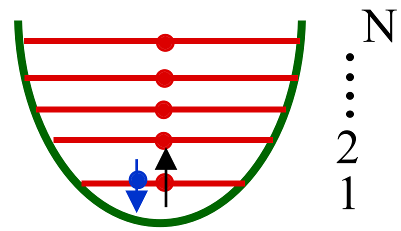
BOSE - Beam



at the lowest possible temperature

Quantum relaxation time $\simeq 10^{-17}$sec

FERMI - Beam



Quantum diffraction - limited volume in phase-space :

$$\boxed{\varepsilon_x^{(n)}\ \varepsilon_y^{(n)}\ \varepsilon_z^{(n)} \geq \left(\frac{\bar{\lambda}_c}{2}\right)^3}$$

$$\bar{\lambda}_c = \frac{\hbar}{mc} = \text{Compton Wavelength}$$

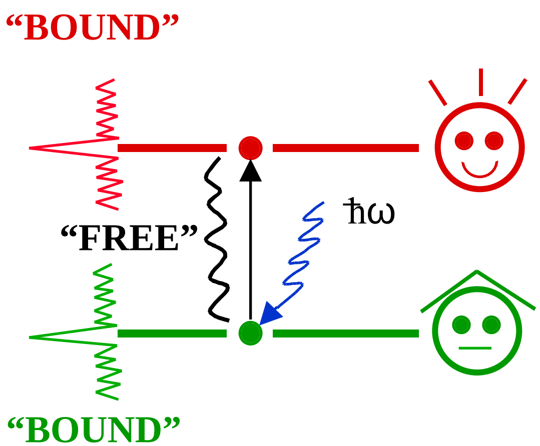
Quantum diffraction-limited volume in phase-space :

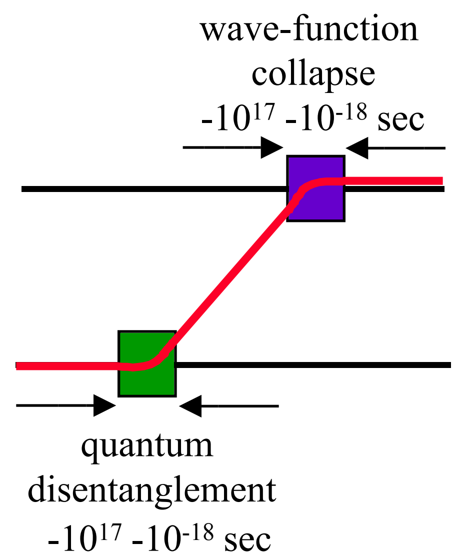
$$\boxed{\varepsilon_x^{(n)}\ \varepsilon_y^{(n)}\ \varepsilon_z^{(n)} \geq \frac{N(\bar{\lambda}_c/2)^3}{(2\ S+1)}}$$

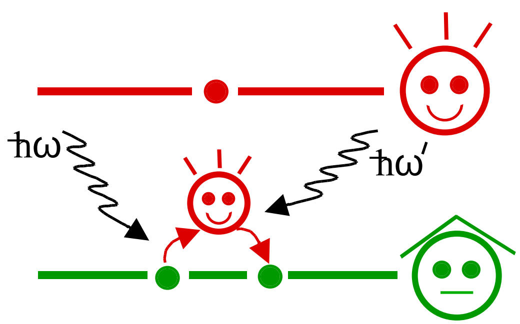
($S \equiv$ spin of the Fermions)

STUDY OF
The Dynamics of Quantum Collapse & Entanglement
via Attosecond Bursts

Although we are comfortable with quantum physics, we seem to be having a hard time with "quantum control". No understanding is complete until one can engineer simple systems.



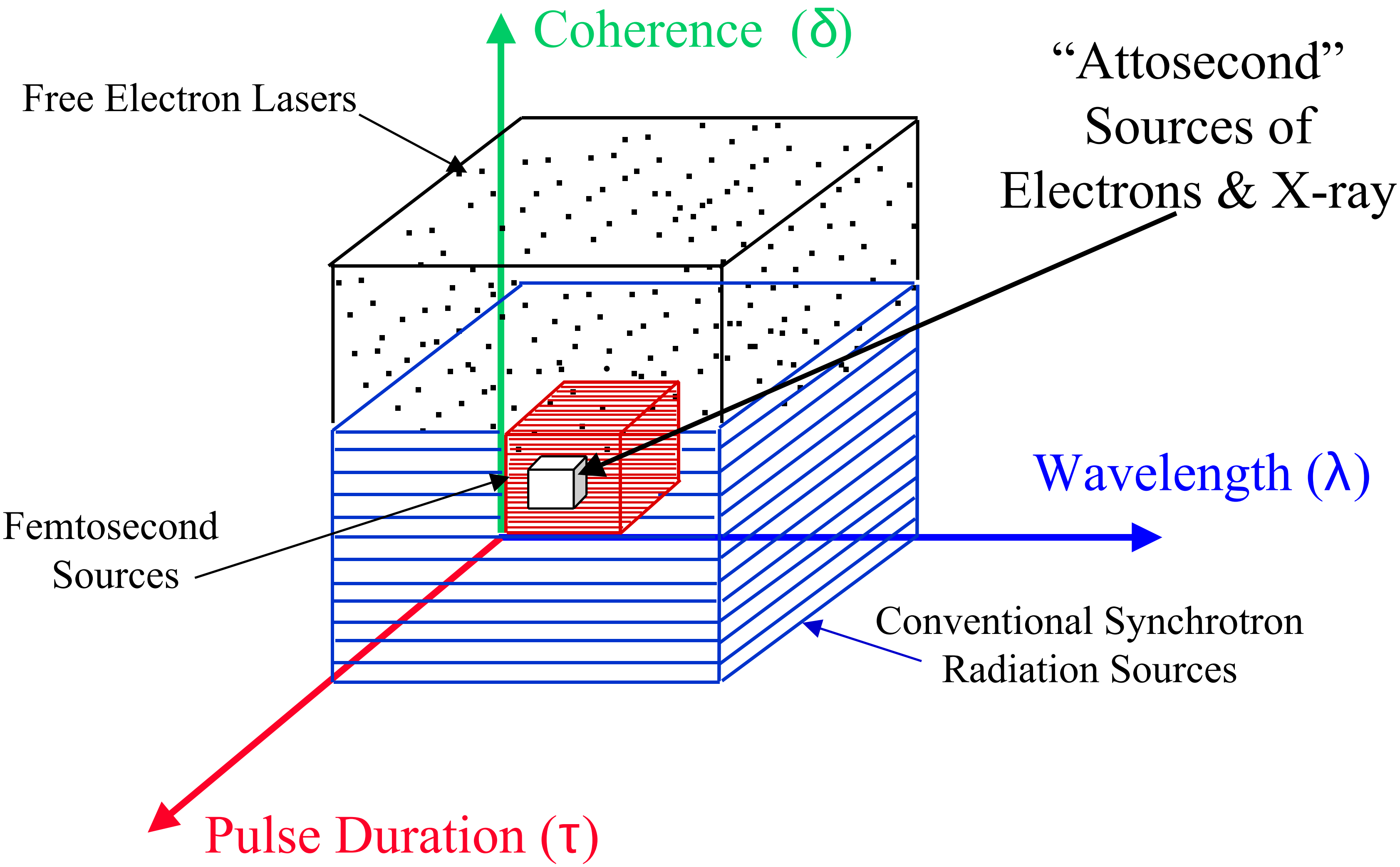




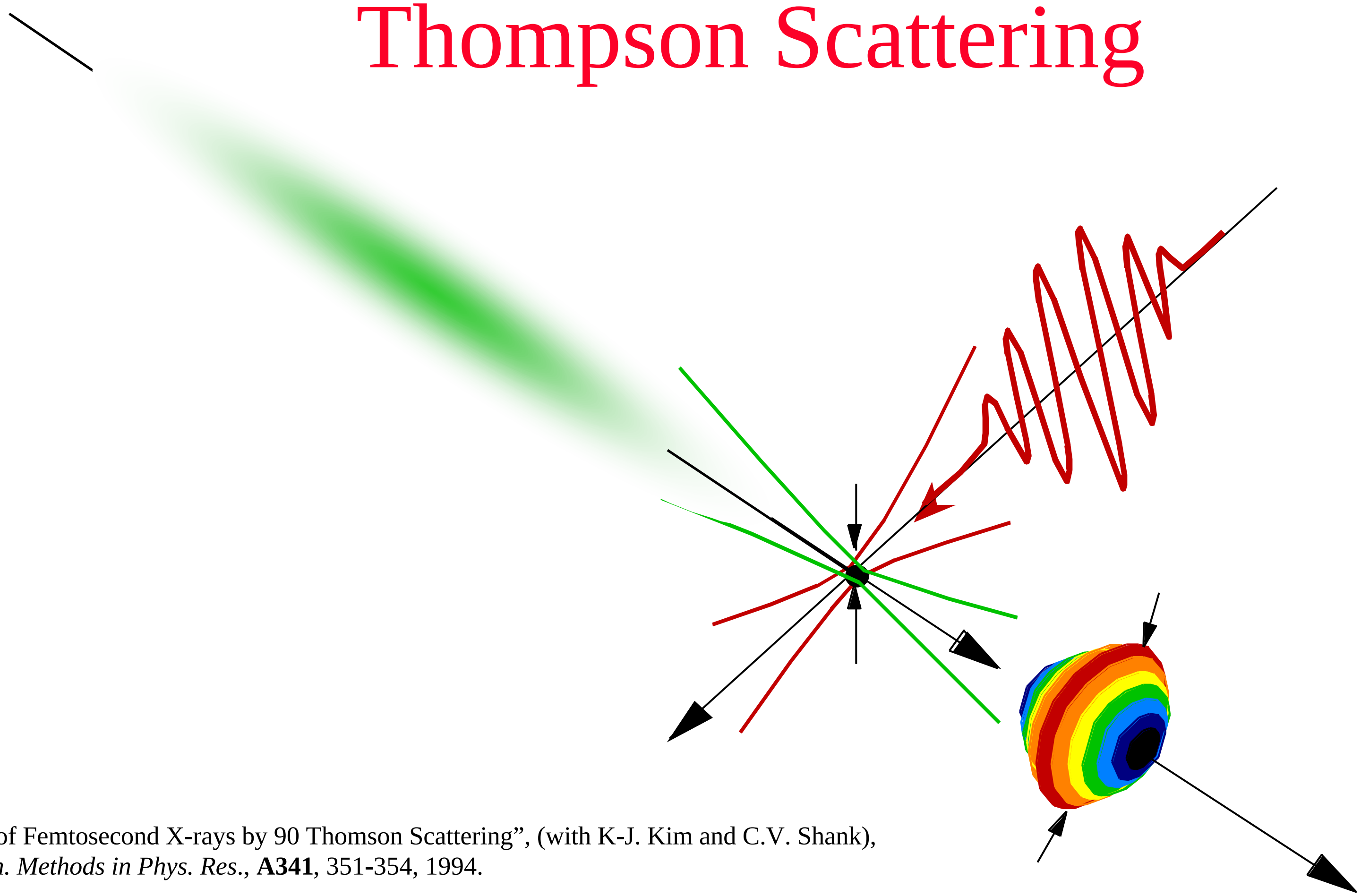
possibility of quantum control & engineering

ULTRASHORT BURSTS

Electron & Radiation Source Characteristics



Thompson Scattering



References:
"Generation of Femtosecond X-rays by 90 Thomson Scattering", (with K-J. Kim and C.V. Shank), *Nucl. Instrum. Methods in Phys. Res*., **A341**, 351-354, 1994.

"Femtosecond X-ray Pulses at 0.4 by 90 Thomson Scattering: A New Tool for Probing the Structural Dynamics of Materials", (with R. Schoenlein, et. al), *Science*, **274**, 11 Oct. 1996., p. 236.

Techniques (con't)

Laser-assisted Atto-bunching:

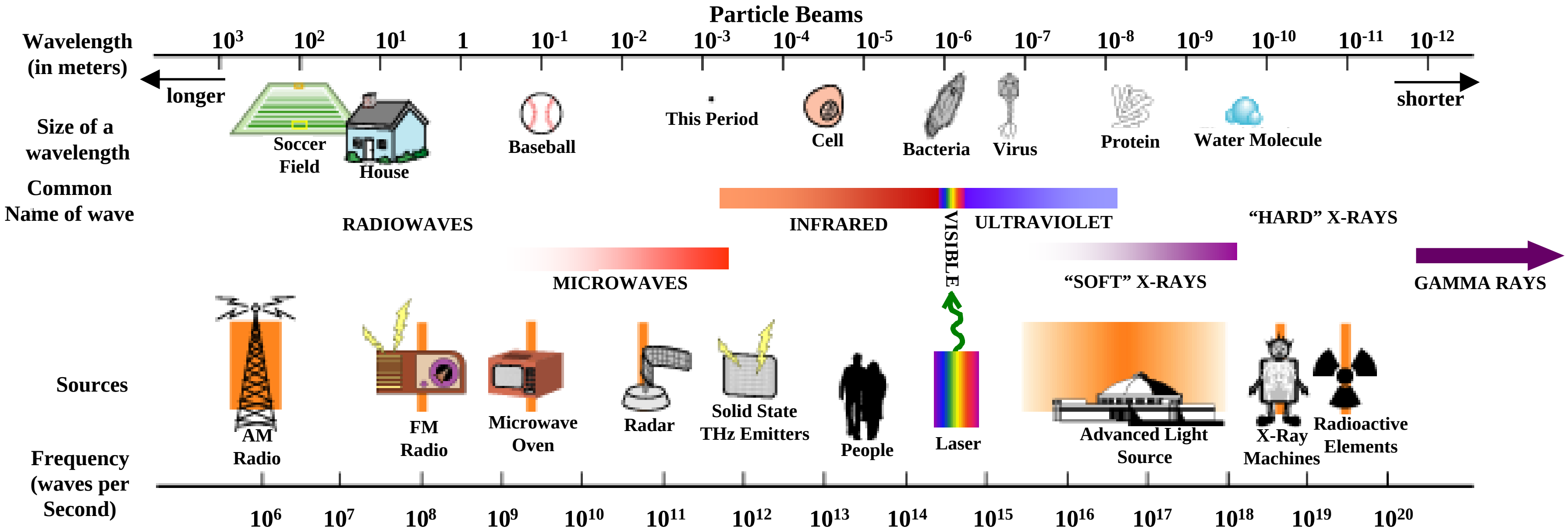
- **Laser-plasma acceleration**
- **Ponderomotive acceleration**

Laser-assisted SASE FEL

Particle Accelerators to date have taken full advantage of the microwave part of

THE ELECTROMAGNETIC SPECTRUM

Pulse Lengths **Spot Size**



Optical Manipulation of Particle Beams

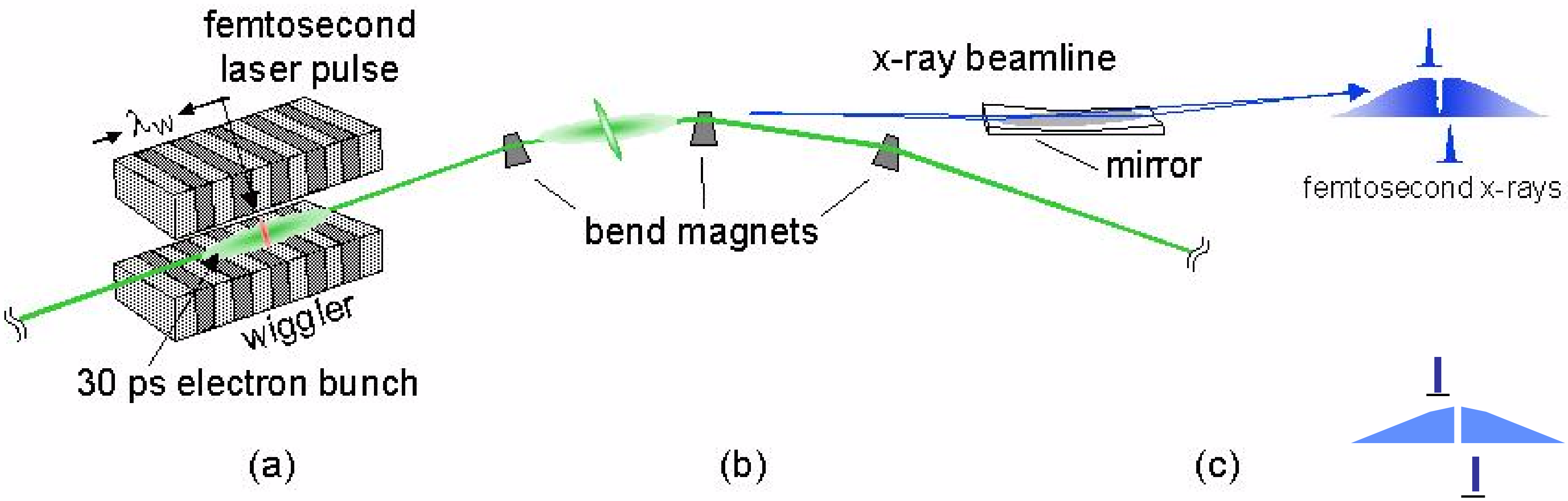
Today we can complement the GHz microwave rf technology by state-of-the-art short pulse high power compact lasers as work horses for particle accelerators.

However, just as in today's microwave technology involving beam manipulation over fractions of mms in time-scales of picoseconds at frequencies of GHz, one would have to learn to manipulate and control signals and particles at optical wavelengths of microns, in time-scales of femtoseconds and at frequencies of THz and higher in order to take advantage of today's optical technology.

The development of femtosecond kickers, choppers, bunch rotators etc., and THz manipulation of beams will be one of the most challenging jobs for future beam applications.

We are encouraged by our recently successful experimental experience.

Laser Femto-slicing of Electron Beams

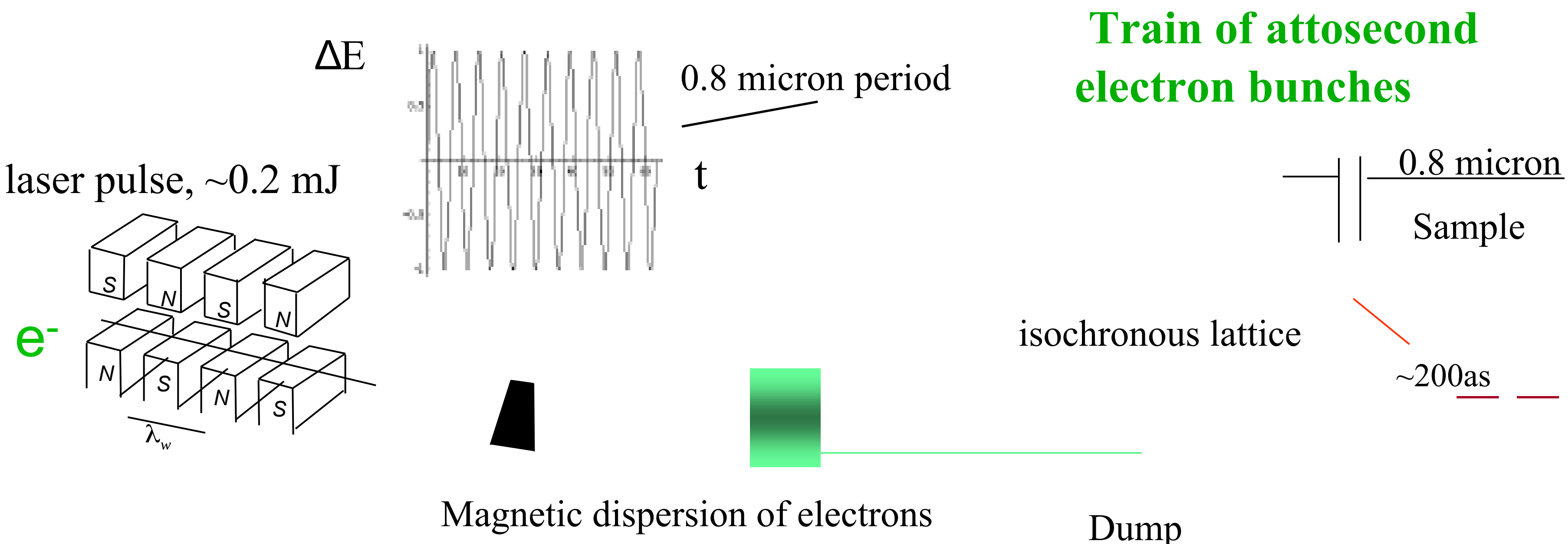


Reference:
Generation of Femtosecond Pulses of Synchrotron Radiation
R. Schoenlein, S. Chattopadhyay, H.H.W. Chong, T.E. Glover, P.A. Heimann, C.V. Shank, A.A. Zholents, M.S. Zolotorev
Science, Vol. 287, No. 5461, March 24, 2000, p. 2237.

→ **Unique experiment in the world.**

→ **Optical Manipulation of Beams**

Atto-Slicing: Laser Slicing Technique



Flux of the attosecond electron bunches:

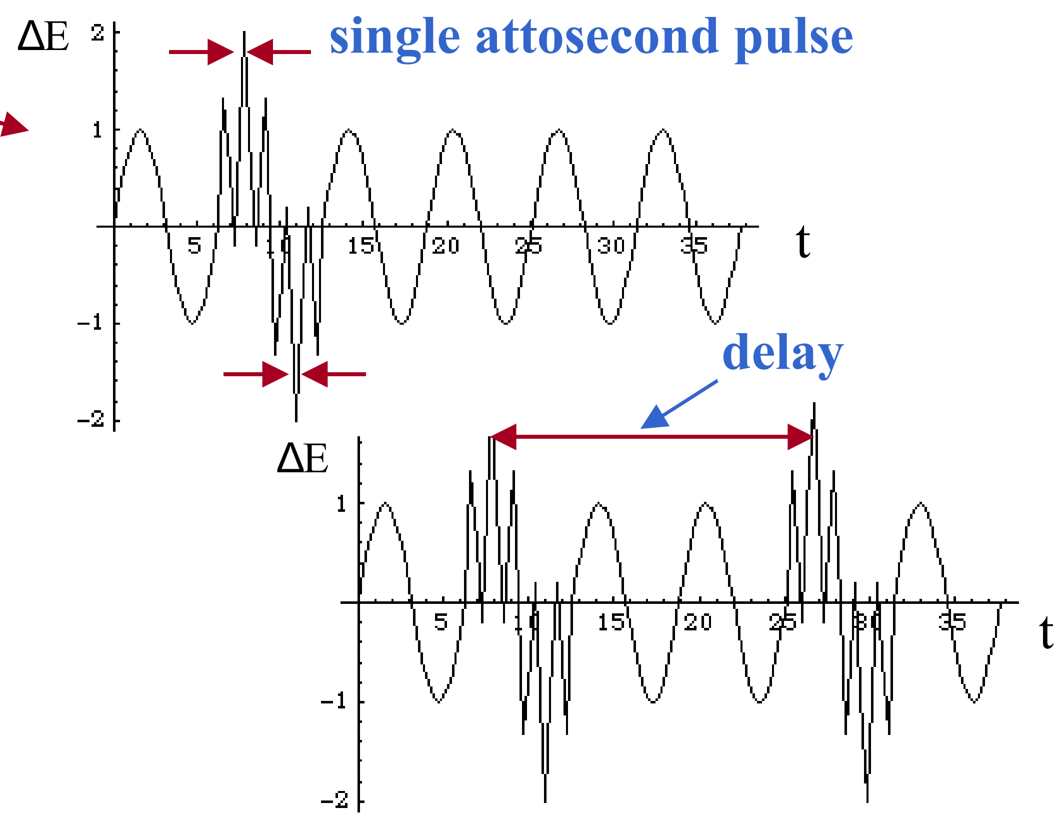
train of ~100 bunches, ~10^6 e/bunch, 10 kHz rep. rate

- **Energy modulation was demonstrated at the ALS for femtosecond x-ray generation**
- **Micro-bunching at 10 μm was demonstrated at ATF/BNL**
- **Electron pulse separation (slicing) down to 0.1 μm must be studied**

Laser Slicing Technique (cont'd)

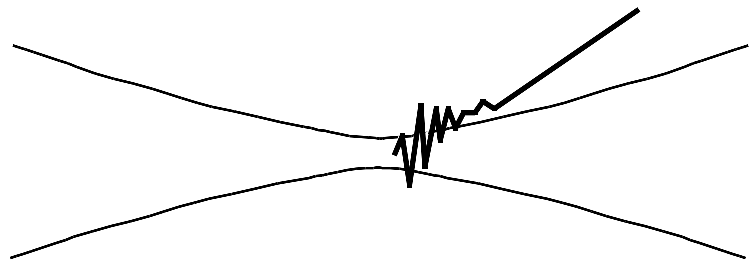
One can also obtain:

- **Two micro-bunch trains using top and bottom peaks of the energy modulation**
- **Single attosecond electron bunch by combining the energy modulation from two lasers**
- **Pulses with variable delay using top and bottom peaks**
- **Pulses with a given delay**



Laser Slicing Technique (cont'd)

Acceleration and Scattering in Intense Laser Field



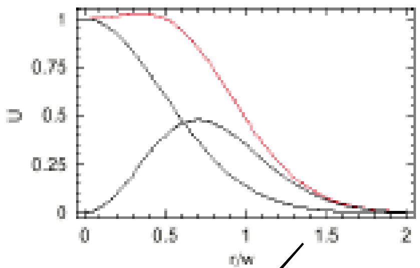
To obtain a high-brightness beam, we want to avoid Scattering during acceleration

Atto-Bunching:
Dynamics of Ponderomotive Laser Acceleration

Laser provides acceleration, focusing and bunching

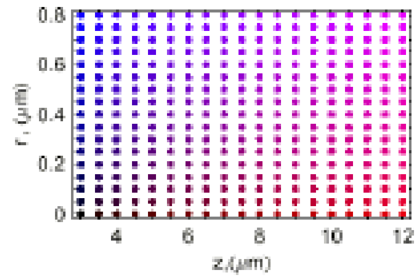
Laser mode

Intensity vs r

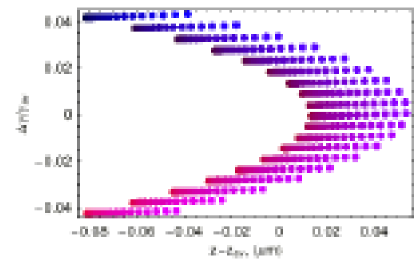


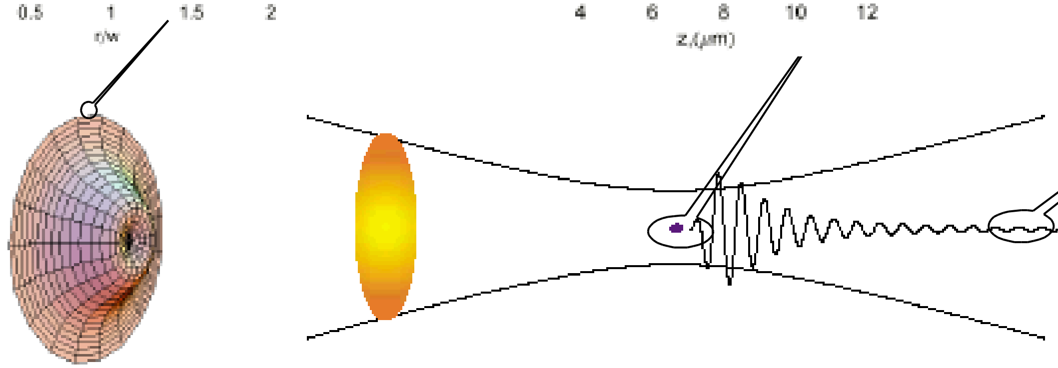
Evolution of longitudinal phase space

Initial (r,z)

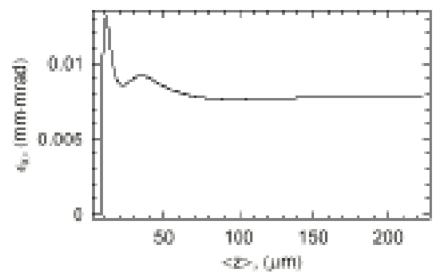


Final (γ,z)

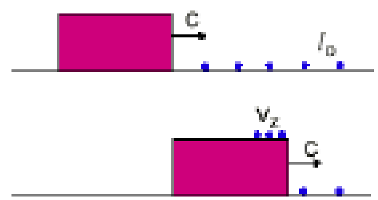




Emittance vs z



Attosecond bunching

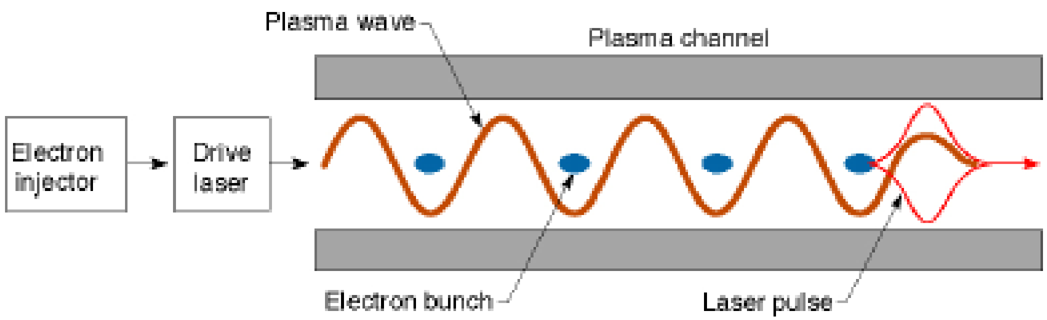


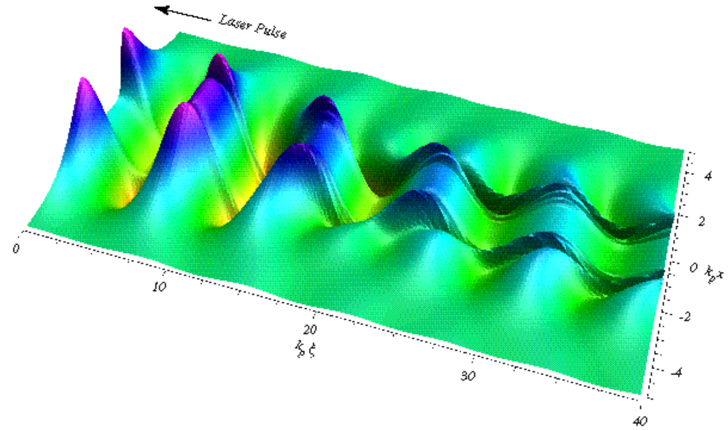
Evolution of transverse phase space

$$l_1 = l_0 \frac{c - v_z}{c} \approx l_0 \frac{1}{2\gamma^2}$$

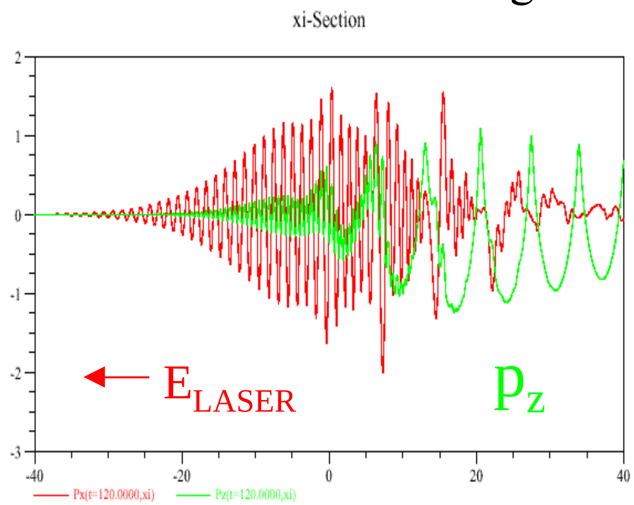
Atto-Bunching: Laser Wake Field Accelerators

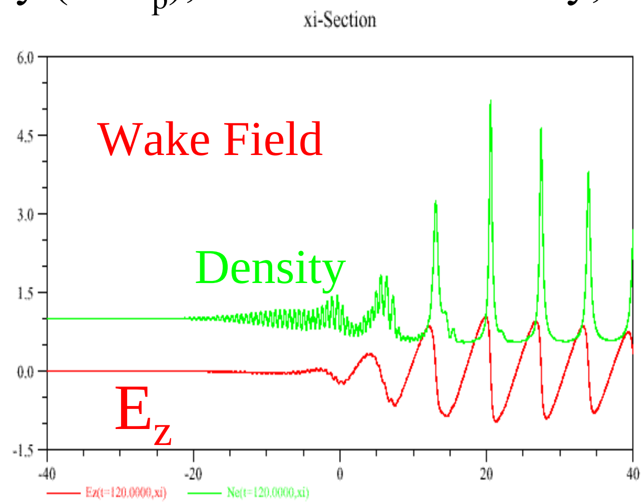
Standard LWFA: Resonant density ($L=\lambda_p$), controlled wake, externally injected electrons





Self-Modulated LWFA: High density ($L>\lambda_p$), wake via instability, self-trapped electrons



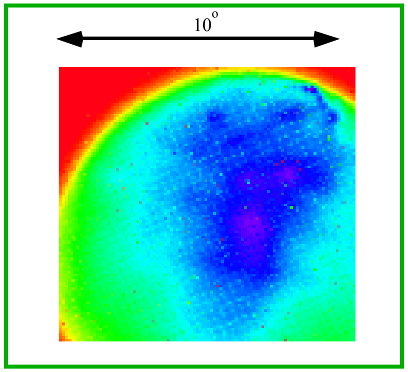


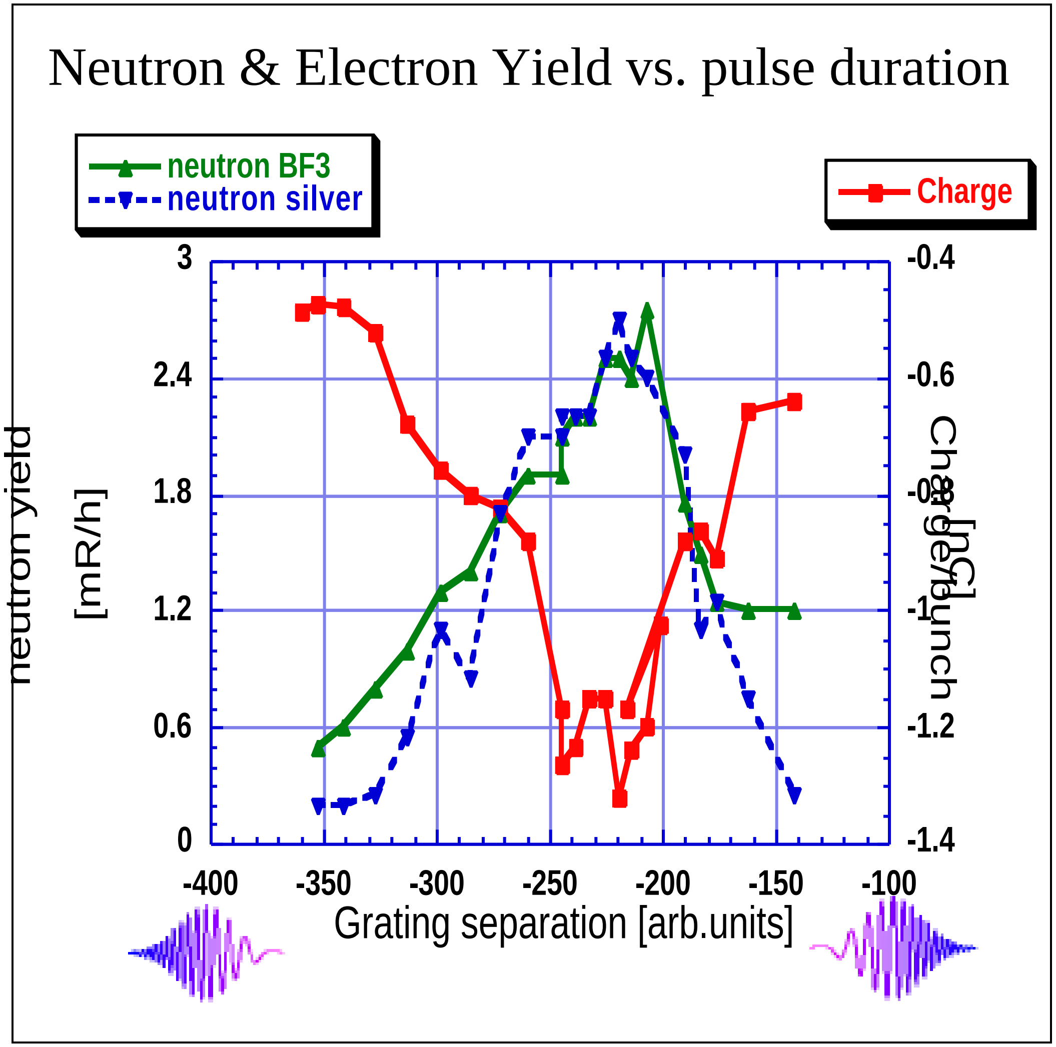
fs microbunches
> 1 nC
100% energy spread

B.A. Shadwick, et.al.

High Energy E-Beam Observed using Self-Modulated LWFA

Electron Beam Images





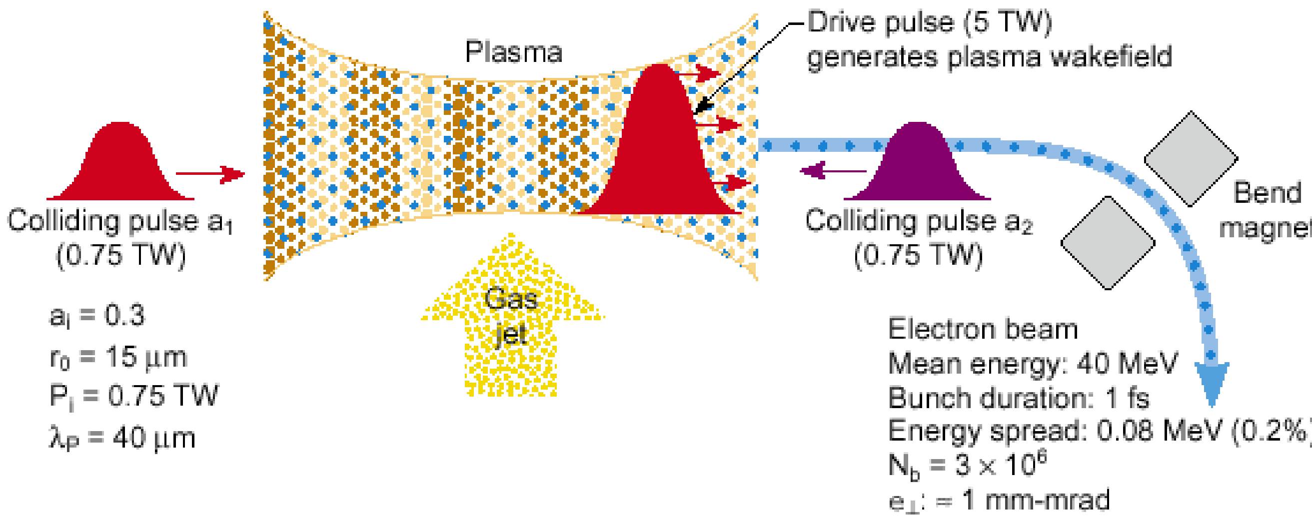
W.P Leemans et al.

Colliding Pulse Injection

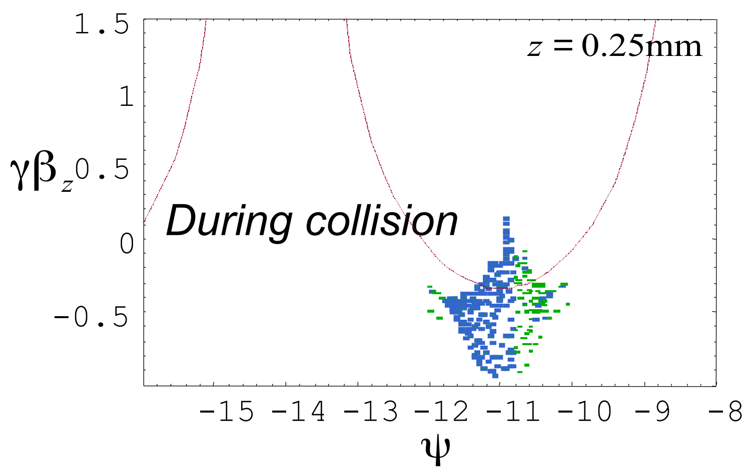
- Standard LWFA regime
- 5 TW drive pulse
- 1+1 TW colliding pulses

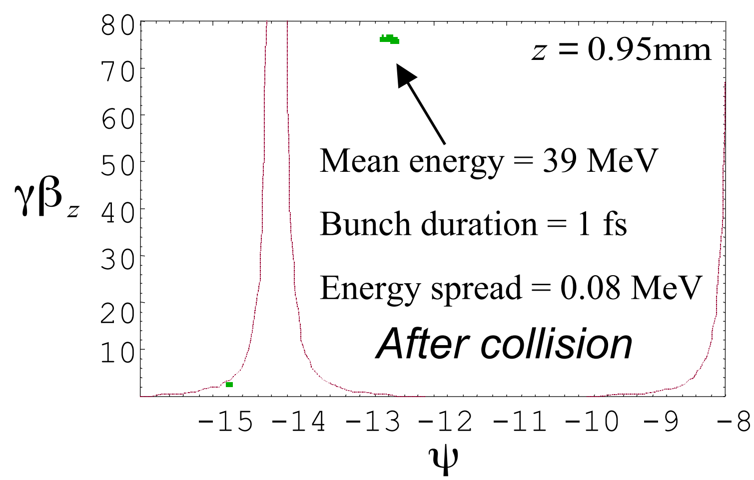
Reference:
E.Esarey et al., PRL '97
C.B. Schroeder et al., PRE '99

Injection pulses collide, producing a slow-moving beat wave that allows electrons to be trapped.

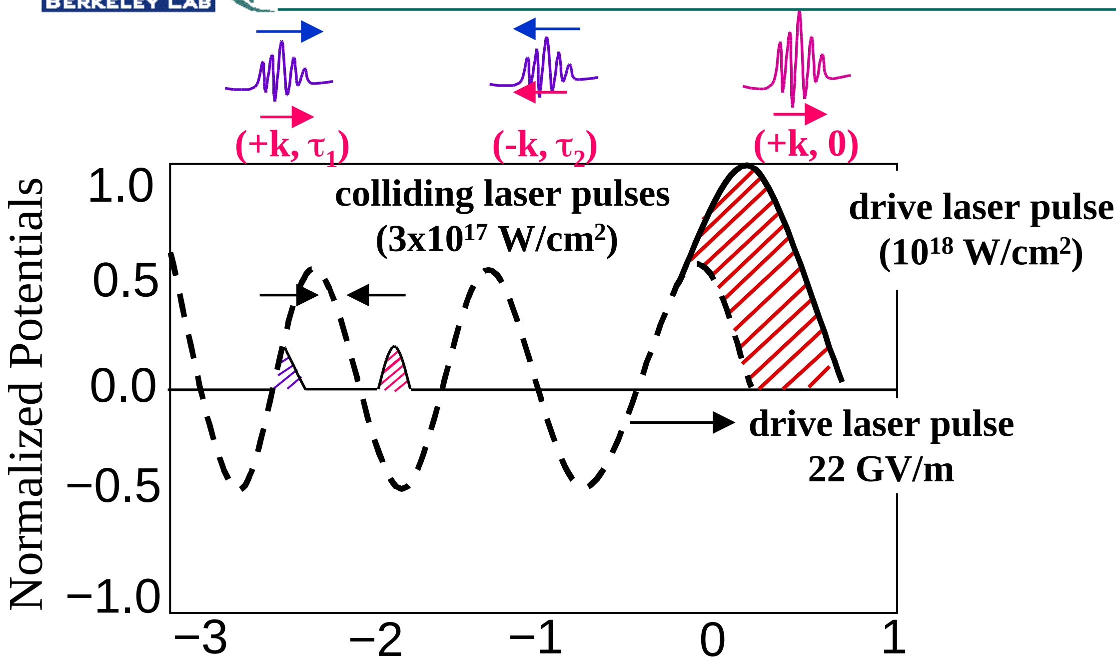


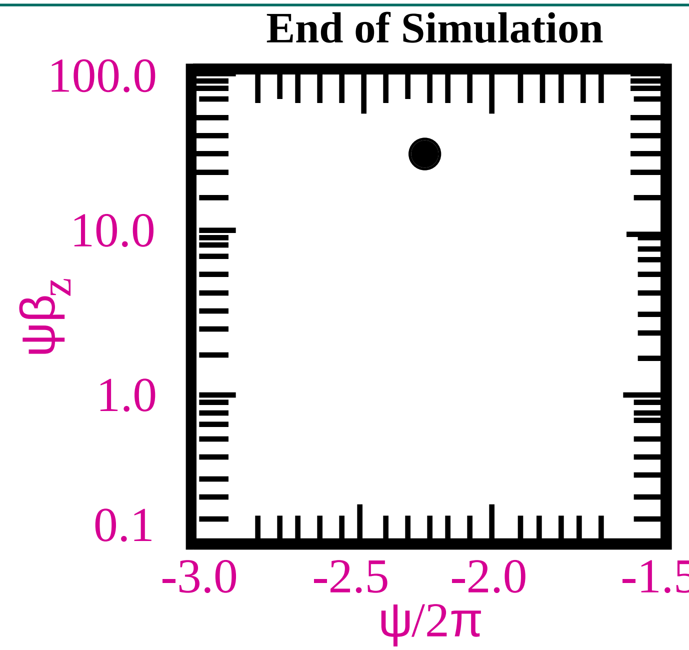
Longitudinal phase space (p_z vs z)

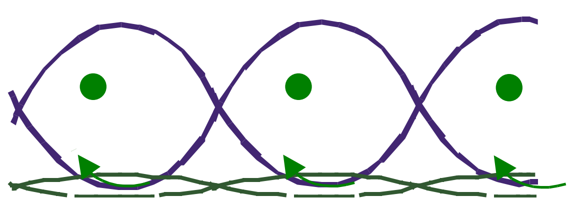




Colliding Pulse Injection







Electron bunch length: 1.0μm (3.4fs)

Electron energy: 27 MeV

Electron energy spread: 0.32%

Trapping fraction: 19%

Bunch density: $n_b \simeq 10^{18} cm^{-3}$

Bunch number: $N_b \simeq 7x10^9$ for r_0~40μm

Table-Top Coherent SASE X-Ray FEL using a Laser Wiggler

FEL x-ray wavelength

$$\lambda_x = \frac{\lambda_w}{4\gamma^2}(1 + a^2)$$

Inverse gain length

$$\frac{1}{2\pi M_g} \approx \frac{1}{1+\varepsilon_b / \varepsilon_x} \sqrt{\frac{1}{2\gamma} \frac{I}{I_A} \frac{a^2}{1+a^2}}$$

Electron beam parameters

$N_e = 10^6$, $c\tau_e = 10^{-6}$ cm, $\varepsilon_{nb} = 10^{-6}$ cm rad

Transverse coherence requirement

$\varepsilon_b / \varepsilon_x < 10$

Examples

SASE E_x=10 keV

THz source (λ_w=100 μm)
γ = 500 (250 MeV)
E_w=20 J
$N_X = 6\text{x}10^8$

SASE E_x=10 keV

CO_2 laser (λ_w=10 μm)
γ = 160 (80 MeV)
E_w=4 J
$N_X = 2\text{x}10^8$

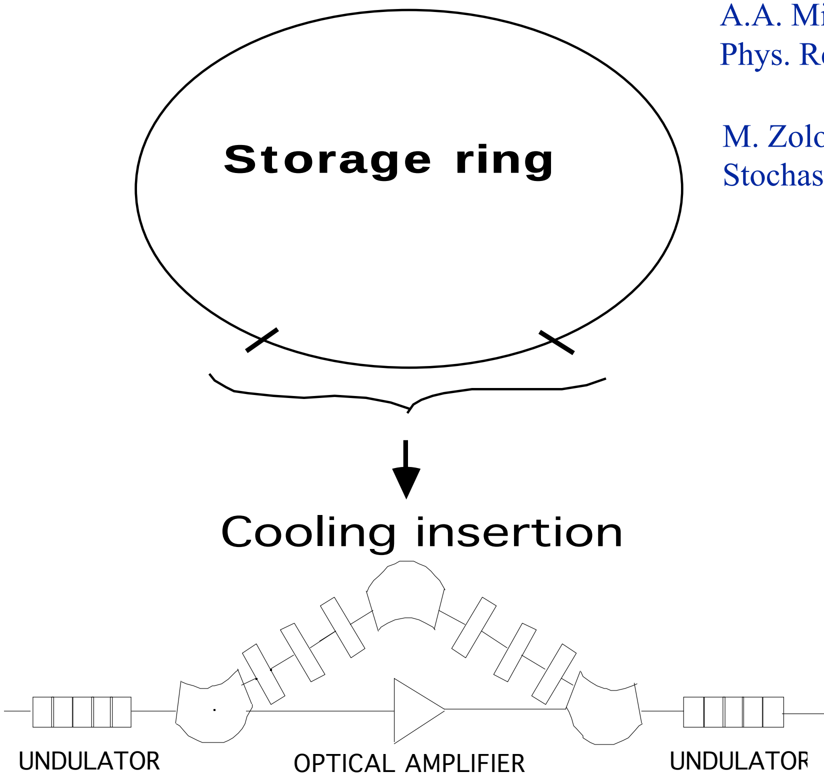
SASE E_x=1 keV

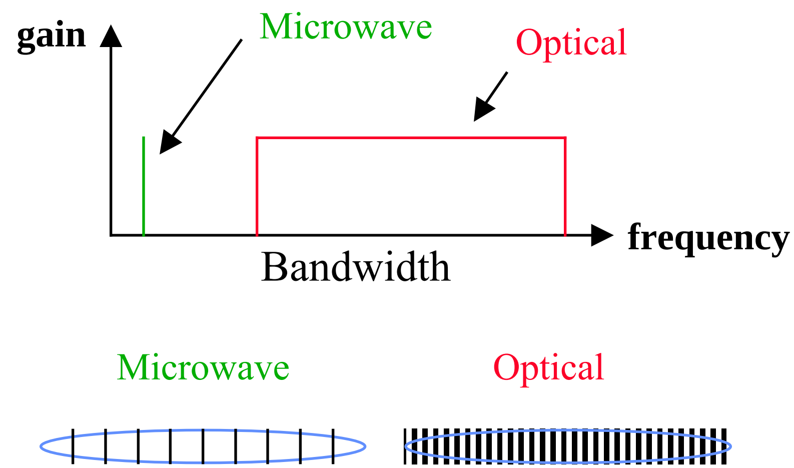
Ti laser (λ_w= 0.8 μm)
γ = 13 (6.5 MeV)
E_w=30 mJ
$N_X = 2\text{x}10^8$

Optical “Control”

A.A. Mikhailichenko and M.S. Zolotorev, “*Optical stochastic cooling*”, Phys. Rev. Lett. , Vol. .71, N25, (1993), p. 4146.

M. Zolotorev and A. Zholents, “Transit-time Method of Optical Stochastic Cooling”, Phys. Rev. E, Vol. 50, No. 4, (1994), p. 3087.





OSC uses optical amplifier and undulators as a pick-up and a kicker.

The amplifier bandwidth is $\sim 10^{13}$ Hz.

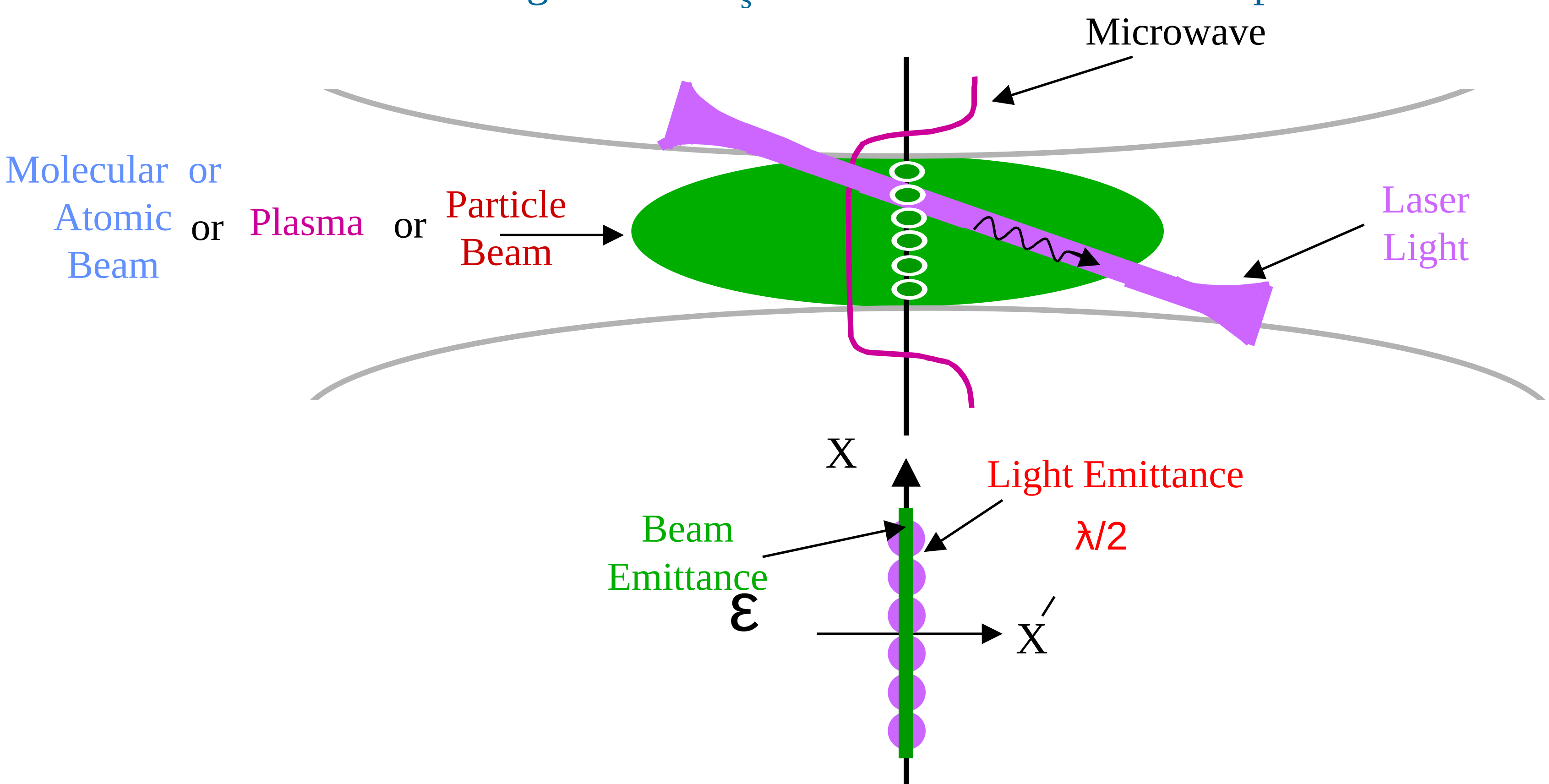
(Compare with $\sim 10^{9}$ Hz for microwave stochastic cooling)

Correspondingly, OSC has a potential for $\sim 10^{4}$ faster damping.

Particle Beam is fully Resolved in Space & Time by Light Beam

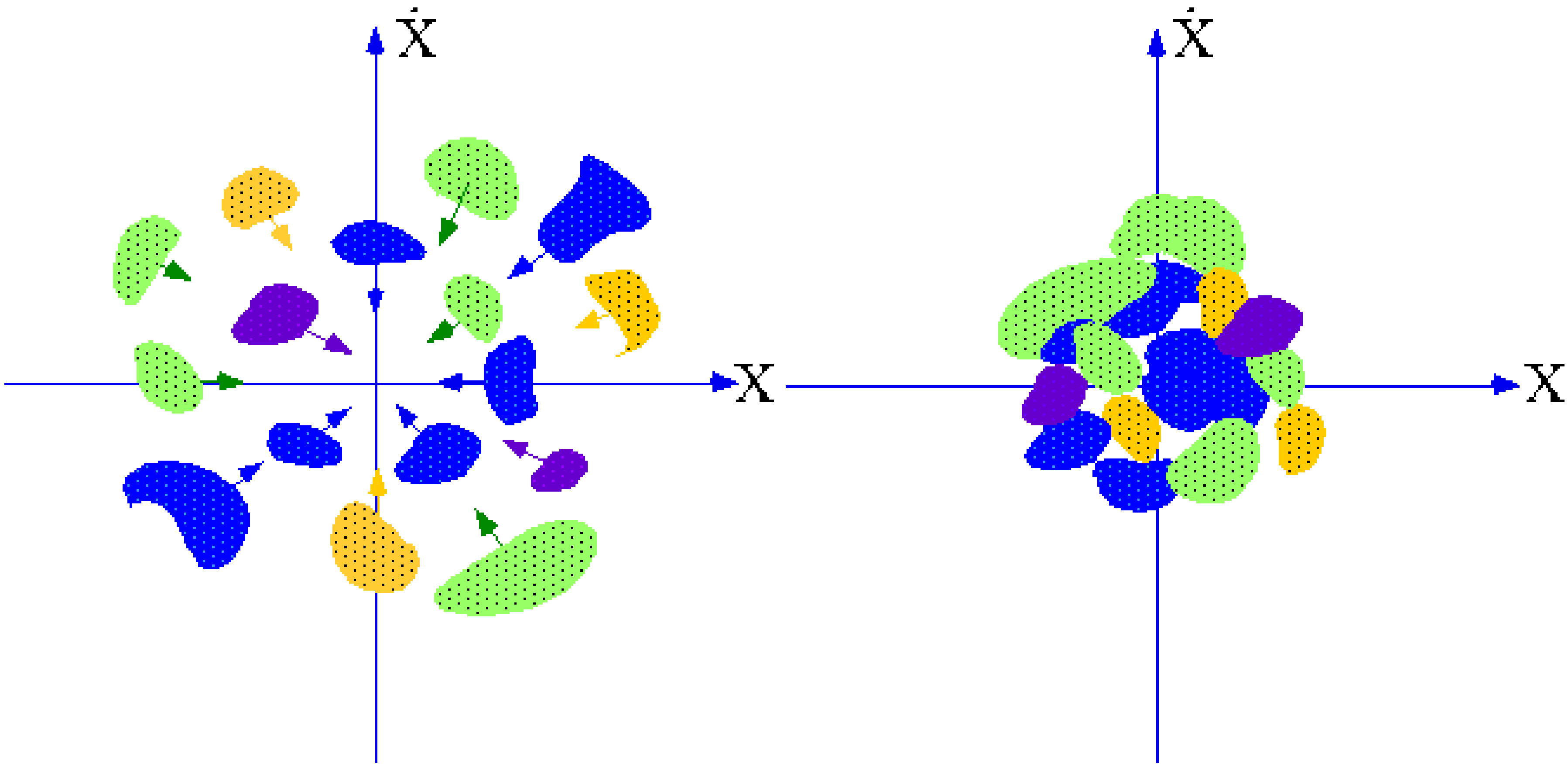
Cooling Rate $\langle \tau \rangle^{-1}$ α Degree of Control in Phase Space α Number of Independent Phase Space Samples Probed $\equiv \frac{N}{N_s}$

Cooling Time $N_s \equiv$ No. of Particles in a Sample



Coherence Volume of Light << Beam Emittance

Phase-Space Cooling in Any One Dimension



Fundamental Issues

We expect: $<\tau>^{-1} \quad \dfrac{1}{[N_s]}$ control time of damping or cooling

But, in practice, there is always amplifier noise which modifies cooling rate to :

$$<\tau>^{-1} \quad \frac{1}{[N_s + N_n]}$$

where $N_n \equiv$ sample population that can generate a noise signal equivalent to the optical amplifier noise

→ → → → **What is N_n ?**

Fundamental Issues

Each particle emits 'α' photons per turn, where $\alpha \equiv$ fine structure constant ~ 1/137

Total no. of equivalent noise photons is ~ $\alpha\, N_n$

Fundamental Issues

Theoretical minimum of optical amplifier noise is <u>one</u> noise photon per optical mode :

$$\alpha N_n \sim 1 \Rightarrow N_n = 1/\alpha$$

$$< \tau >^{-1} \simeq \frac{1}{[N_s + (1/\alpha)]}$$

Fundamental Issues

For large sample population, $N_s \sim 10^7 - 10^9$,
the number of equivalent
photons from sample and amplifier :

$$N_p = \alpha\, N_s + \alpha N_n \sim (10^5 - 10^7) + 1 >> 1.$$

This large no. of photons generate an electric field in the far-field regime which is describable as classical light

Large "degeneracy parameter": large number of photons in a coherence volume

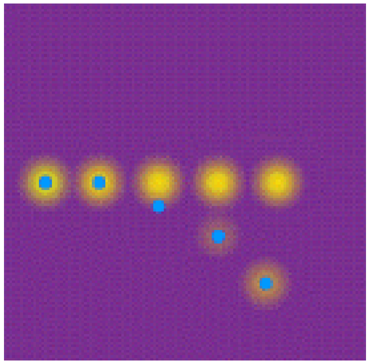
Fundamental Issues

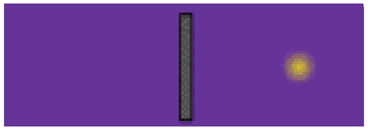
For small sample population, $N_s \sim 50 - 100$,
the number of equivalent
photons from sample and amplifier :
$N_p \sim (0.5 - 1) + 1 \sim O(1)$.
These few photons generate a field which
is intrinsically non -classical and quantum mechanical.

Small "degeneracy parameter": small number of photons in a coherence volume

How does optical control work in
this quantum limit ??

Radiation for Charged Particles—
A Simple Physical Vision





http://www.lbl.gov/educational sites/The World of Beams

Fundamental Issues

Understanding "Quantum Optics"
driven by
accelerated charges would
be critical
in these studies